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MICROSCOPY IMAGING APPARATUS AND MEHOD FOR GENERATING AN IMAGE

The present invention relates to a microscopy imaging
5 apparatus and a method for generating an image, and in
particular an apparatus and method for generating an
optically sectioned image.

With a conventional wide-field microscope it is not
possible to obtain a proper two-dimensional optically
10 sectioned image of a three dimensional specimen because the
resultant image contains contributions from out-of-focus
specimen structures above and below the specimen object
plane which blur the image of the specimen object plane.
Conventional wide-field microscopes are unable to reject
15 these out-of-focus details.

To overcome this problem confocal microscopes have
been developed. These devices use a point light source
located in a plane which is optically conjugate to the
specimen object plane. This arrangement allows out-of-
20 focus light to be rejected, but the illuminating light beam
has to be laterally scanned to build up the optically
sectioned image point-by-point. This leads to long
acquisition times, particularly if it is desired to "stack"
optically sectioned images obtained at successive focal
25 positions to form a three dimensional image of the
specimen. Also the light efficiency of such devices tends
to be low.

In order to avoid scanning and to reduce acquisition
times a number of approaches have been suggested. One of
30 these involves the use of a Nipkow disk in which the
pinhole is replaced by a multi-aperture rotating disk that
enables parallel observation of several confocal volumes.
Even so, only about 2% of the total illumination light
budget is used for imaging.

In an attempt to overcome this problem, Verveer et al. (Verveer P.J., Gemkow M.J. and Jovin M., *J. Microscopy*, Vol. 189(3), (1998), 192-198), proposed replacing the Nipkow disk with a digital micro-mirror device which serves as a programmable pinhole array. The image thus-obtained consists of superimposed confocal and conventional images. The pure confocal contribution is recoverable by subtracting the conventional image, but at the cost of increasing noise.

WO 98/45745 discloses an alternative approach in which an object is illuminated by a periodic pattern and at least three specimen images are recorded at different spatial phases of the pattern. The three images are then combined by image processing which removes the periodic pattern and out-of-focus contributions, and thereby produces an optically sectioned image. However, this approach is not convenient for implementing real-time imaging.

An object of the present invention is to provide a method of generating an optically sectioned specimen image which, like conventional confocal techniques, comprises substantially only in-focus detail, but has a more favourable light budget and acquisition time. A further object is to provide a method of generating an optically sectioned specimen image which facilitates real-time imaging.

In a first aspect, the present invention provides a method of generating an optically sectioned image of a specimen comprising the steps of: illuminating the specimen with a modulating, spatially periodic illumination pattern; imaging said specimen on a conjugate image plane; acquiring a plurality of signals at respective positions on said image plane, each signal (which is typically an electrical signal) corresponding to the incident light intensity at that position and having an oscillatory component caused by the modulation of the illumination pattern; and measuring a

characteristic (typically the amplitude) of the oscillatory component of each of the signals, whereby the measured characteristics when combined in their relative positions generate an optically sectioned image of the specimen.

5 Thus, the present invention is based on the realisation that analysis of the temporal variation of the light from the specimen allows out-of-focus contributions to be rejected. Such analysis is amenable to automated processing, which opens the door to real-time imaging.

10 This is in contrast to the approach of WO 98/45745 where discrete images rather than temporal variations are analysed.

15 Preferably the method further comprises a step, between the acquisition and measuring steps, of filtering each acquired signal to isolate the oscillatory component therefrom.

20 Typically, the optically sectioned image will be pixellated, the value (e.g. brightness or colour value) of each image pixel being determined by the measured characteristic of the respective oscillatory component, and the position of each pixel corresponding to a respective position on the image plane.

25 The method may be repeated for different focal positions to produce a series of optically sectioned images of the specimen. These can then be combined to form a three-dimensional image of the specimen.

30 Preferably, the spatially periodic illumination pattern is modulated to produce a predetermined modulation frequency at respective specimen positions, whereby the oscillatory components of the signals acquired at corresponding positions on the image plane have substantially the same frequency. By the "modulation frequency" we mean the reciprocal of the time required for a position on the specimen to undergo one complete

illumination cycle from light to dark and back to light again.

In preferred embodiments, the illumination pattern has one-dimensional periodicity. For example the pattern may be a fringe pattern e.g. comprising parallel linear fringes or concentric circular fringes. Such patterns have well-defined spatial periodicities and may be produced e.g. by interferometry or by an illuminated mask. They can also be modulated by moving or shifting the elements of the patterns in such a way to ensure that substantially all imaged specimen positions experience substantially equal modulation frequencies and time-integrated illumination intensities.

For example, a pattern of parallel linear fringes may be moved by shifting the fringes across the specimen in the direction lateral to the fringes, the modulation frequency is then the inverse of the time taken to shift the fringes by one fringe spacing. A pattern of concentric circular fringes may be moved by expanding the fringes away from or contracting them towards the common centre of the fringes, the modulation frequency being the inverse of the time taken for a fringe to grow (or shrink) to the size of the adjacent fringe.

Preferably, the illumination pattern is modulated to produce a modulation frequency of at least 100 Hz (more preferably of at least 1 kHz, 10 kHz or 100 kHz).

Typically the incident light at the image plane comprises reflected or transmitted light, and/or light emitted by the specimen (such as fluorescent light) in response to the illumination pattern.

A further aspect of the present invention provides a method of processing image data to generate an optically sectioned image comprising: (a) receiving data which comprises a plurality of signals previously acquired by performing the steps of (i) illuminating a specimen with a

modulating, spatially periodic illumination pattern, (ii) imaging said specimen on a conjugate image plane, and (iii) acquiring a plurality of signals at respective positions on said image plane, each signal corresponding to the incident light intensity at that position and having an oscillatory component caused by the modulation of the illumination pattern; and (b)

measuring a characteristic (typically the amplitude) of the oscillatory component of each of the signals, whereby the measured characteristics when combined in their relative positions generate an optically sectioned image of the specimen.

Thus this aspect of the invention relates to the processing of image data previously acquired by performing the illumination, imaging and acquisition steps of the previous aspect. Optional and preferred features of the previous aspect apply also to this aspect.

For example, the method may further comprise a step, between the receiving and measuring steps, of filtering each acquired signal to isolate the oscillatory component therefrom.

A further aspect of the invention provides a microscopy imaging apparatus comprising: illumination means for illuminating a specimen with a modulating, spatially periodic illumination pattern; imaging means for imaging said specimen on a conjugate image plane; acquisition means for acquiring a plurality of signals at respective positions on said image plane, each signal corresponding to the incident light intensity at that position and having an oscillatory component caused by the modulating illumination pattern; and processor means for measuring a characteristic (typically the amplitude) of the oscillatory component of each of the signals, whereby the measured characteristics when combined in their relative positions generate an optically sectioned image of the specimen.

Preferably the processor means also filters each acquired signal to isolate the oscillatory component therefrom prior to measuring the characteristic of the oscillatory component.

5 In one embodiment, the illumination means comprises means for generating a spatially periodic interference illumination pattern, such as may be generated by two overlapping coherent beams of light. The coherent beams of light may be produced by a laser or lasers.

10 Alternatively the illumination means may comprise a light source which illuminates the specimen through a patterned grid, the grid pattern corresponding to the illumination pattern. Such a source may be incoherent. Furthermore, it may illuminate the specimen with white
15 light.

The acquisition means may comprise an array of light detectors for respectively detecting light intensity at the plurality of image plane positions. Typically such detectors operate in parallel. Suitable one- and two-
20 dimensional signal detector arrays are described in EP-A-1065809. If a one-dimensional array is used, generation of a two-dimensional optically sectioned image requires the array to be scanned across the image plane. Preferably, however, a two-dimensional array is used so that light
25 intensities across substantially the whole image plane are detected simultaneously. This reduces the image acquisition time.

With a two-dimensional array of detectors, each detector may acquire a signal corresponding to one pixel of
30 a pixellated optically sectioned image. With a one-dimensional scanned array of detectors, each detector may acquire signals corresponding to a line of pixels of a pixellated optically sectioned image

Preferably, the processor means comprises a plurality
35 of signal processors for respectively measuring (and

optionally filtering) the oscillatory components of the acquired signals. Typically the processors operate in parallel to reduce the image generation time.

More preferably, with an array of signal detectors, each signal detector has a dedicated signal processor, e.g. as described in EP-A-1065809. Thus signal acquisition, filtering and subsequent measurement can be fully automated.

Typically the illumination means modulates the illumination pattern to produce a predetermined illumination modulation frequency (e.g. of at least 100 Hz, 1 kHz, 10 kHz or 100 kHz). Preferably the processor means is adapted to filter the acquired signals at substantially the same frequency in order to isolate effectively the oscillatory components from the signals.

A further aspect of the invention provides a conversion kit for converting a conventional microscope into the microscopy imaging apparatus of the previous aspect, the conversion kit comprising: illumination means for illuminating a specimen with a modulating, spatially periodic illumination pattern; acquisition means for acquiring a plurality of signals at respective positions on a conjugate image plane onto which the microscope images the specimen, each signal corresponding to the incident light intensity at that position and having an oscillatory component caused by the modulating illumination pattern, and processor means for measuring a characteristic (typically the amplitude) of the oscillatory component of each of the signals, whereby the measured characteristics when combined in their relative positions generate an optically sectioned image of the specimen.

Preferably the processor means filters each acquired signal to isolate the oscillatory component therefrom prior to measuring the characteristic of the oscillatory component.

The kit may have other preferred or optional features corresponding to preferred or optional features of the microscopy imaging apparatus of the previous aspect.

Specific embodiments of the present invention will now be described with reference to the accompanying drawings in which:

Fig. 1 shows the absolute value of the optical transfer function OTF as a function of the generalised distance to the focal plane $u = 4\pi w / \lambda$ and the generalised spatial frequency $v = \lambda / (n \sin \alpha \cdot f)$,

Fig. 2 is a flow chart which shows schematically the signal detection and processing steps performed by a detector/processor pair of an amplitude demodulation detector array (ADDA),

Fig. 3 shows a typical detector/processor pair frequency response,

Fig. 4 shows a microscopy imaging apparatus according to a first embodiment of the present invention, and

Fig. 5 shows a microscopy imaging apparatus according to a second embodiment of the present invention.

A spatially periodic illumination pattern comprising linear parallel fringes may be formed e.g. by interference between two mutually coherent light beams. The interference fringes are formed by planes of uniform illumination intensity extending essentially parallel to the optical axis. Thus on any plane perpendicular to the optical axis (such as the focal plane) the fringes appear as an interference pattern having a period given by the magnitude of the wave shift vector, $\Delta \vec{k} = \vec{k}_1 - \vec{k}_2$, resolved onto that plane, where \vec{k}_1 and \vec{k}_2 being the k-vectors of the two laser beams.

The resulting specimen illumination intensity, I_{ex} , is given by:

$$I_{ex}(\vec{r}, \varphi) = 1 + \cos(2\Delta \vec{k} \vec{r} + \varphi),$$

where \vec{r} is a position vector in a plane perpendicular to the optical axis, and ϕ is the phase lag produced when the fringes are modulated by being shifted in a direction lateral to the fringes. The value of ϕ is thus a function of time, t . For example, if f is the illumination modulation frequency, the fringes are moved laterally by a whole fringe period in a time $1/f$, so $\phi = 2\pi t f$.

The illumination pattern causes (e.g. reflected, transmitted or fluorescent) light to originate from the specimen, the light having an intensity which is proportionate to I_{ex} and also to the specimen three-dimensional optical object structure, $o(\vec{r})$. Thus the image intensity, I_{im} , can be written as:

$$I_{im}(\vec{r}, \phi) = o(\vec{r})I_{ex}(\vec{r}, \phi) * p(\vec{r}),$$

where $p(\vec{r})$ is the incoherent point spread function and $*$ denotes a convolution.

In k -space this can be written as:

$$I_{im}(\vec{k}, \phi) = O(\vec{k})P(\vec{k}) + \frac{1}{2} [e^{i\phi} O(\vec{k} + \Delta\vec{k}) + e^{-i\phi} O(\vec{k} - \Delta\vec{k})] P(\vec{k}),$$

where \vec{k} is reciprocal distance, $P(\vec{k})$ is the optical transfer function (OTF), and O is the image frequency spectrum. The first term, $O(\vec{k})P(\vec{k})$, corresponds to an image obtained using a conventional microscope, while the second term contains the image frequency spectrum shifted towards higher spatial frequencies. Only the second term is dependent on the phase lag, ϕ , of the fringe system. Effectively, the first term may be thought of as a DC component and the second term may be thought of as an AC or oscillatory component.

In the second term, the frequency shifted image spectrum is multiplied by the OTF. Fig. 1 shows the absolute value of the OTF according to an approximation given by Stokseth (A. Stokseth, *Journal of the Optical Society of America*, Vol. 59(10), (1969), 1314-1321) as a

function of the generalised distance to the focal plane
 $u = 4\pi w / \lambda$ and the generalised spatial frequency
 $v = \lambda / (n \sin \alpha \cdot f)$, where w is the optical path length, λ is
the optical wavelength, $n \sin \alpha$ is the numerical aperture and
5 f is the spatial frequency. Out-of-focus contributions
(i.e. contributions originating from specimen positions
distant from the focal plane) are attenuated much more
heavily than in-focus contributions (i.e. when $u = 0$).

The theoretical model discussed above is based on the
10 well-known approach of describing imaging in terms of
reciprocal k -space. For simplicity we have used the
example of coherent illumination. However incoherent
illumination can be adopted in a straightforward manner
instead. For example, the linear parallel fringes may be
15 formed by illuminating an appropriate mask and imaging the
mask onto a focal plane coincident with the specimen.

Consistent with the theoretical model, we can also
describe the optical sectioning effect achieved by the
present invention by a simple qualitative model in real x -
20 y - z space, where the optical axis corresponds to the z -
axis. Effectively, the moving periodic illumination
pattern is only "visible" (in the sense of having strong
contrast) in the imaged specimen within an optically
sectioned volume which extends across an x - y plane. The
25 visibility of the pattern drops off sharply along the
optical axis in other x - y planes to either side of the
optically sectioned volume. That is, away from the
optically sectioned volume the pattern washes out and
eventually forms non-periodic background illumination which
30 contributes to the above-mentioned DC component.

Thus moving out of focus means losing fringe contrast
and movement. Hence only those parts of the specimen
within the optically sectioned volume modify (e.g. by
reflection, transmission or fluorescence) the illuminating

light in such a way as to result in a light signals which have oscillatory components. These can be measured as AC signals which can then be used to construct an optically sectioned image.

5 Thus optical sectioning can be achieved by locating an array of light detectors on the conjugate image plane and splitting the signal acquired at each detector into a DC and an AC component. The DC component corresponds to the time-invariant conventional microscope image and can be
10 ignored, whereas the AC signal carries substantially only in-focus spatial frequency components and can be used to generate an optically sectioned image.

 A suitable detector array is the amplitude demodulation detector array (ADDA) described in EP-A-
15 1065809. The ADDA is formed on a silicon chip as a two-dimensional array of photo sensor light detectors and corresponding integrated circuit signal processors. Each signal/processor pair corresponds to one pixel of the final optically sectioned image whereby effectively instantaneous
20 acquisition of a complete image can be achieved.

 An advantage of using ADDAs is that all the signal processing functions can be performed by integrated circuitry on the silicon chips. ADDAs also have low sensitivity to power fluctuations.

25 Fig. 2 is a flow chart which shows schematically the signal acquisition and processing steps performed by each detector/processor pair of an ADDA. The photosensor 1 captures the light and generates a corresponding electrical signal. The amplifier 2 together with the low-pass filter
30 3 and current source 4 provide a feedback loop which results in the rejection of the DC component of the electrical signal and amplification of the AC component. The AC component is then rectified at rectifier 5 and a final stage low-pass filter 6 further filters and smoothes
35 the AC component.

The analog output of the detector/processor pair is therefore effectively a measurement of the amplitude of the AC component, and can then be sent to an analog/digital converter for combination with the outputs from the other pairs into the optically sectioned image. The image may be displayed, for example, on a video monitor (with the AC component amplitude measurements converted into e.g. pixel brightness levels) or stored on a computer-readable memory device (such as a hard disc, RAM, CD etc.).

Fig. 3 shows a typical detector/processor pair frequency response. The response provides DC signal suppression and an AC signal pass band which has a maximum frequency response at about 200 kHz. For optimum compatibility with an ADDA array formed of such pairs, the illumination pattern should be modulated so that the illumination modulation frequency is 200 kHz.

An advantage of such a frequency response is that image noise contributions for the conventional microscope image are also suppressed.

Fig. 4 shows a microscopy imaging apparatus according to a first embodiment of the present invention. Light is produced by a coherent light-source 11 such as a laser, and is optionally attenuated by an optional attenuator 12. This light is split into two parallel beams at beam separator 13 and mirror or prism 14. Next, phase or frequency shifting elements 15 and 16 respectively operate on the beams. The two shifted beams are then recombined by mirrors 17 and 18 at the specimen 19 to form a continuously moving periodic illumination pattern which provides a uniform illumination modulation frequency at each point on the specimen 19.

The light from the specimen is then imaged through lenses 20 and 21 (which may be for example a conventional wide field microscope observation stage arranged in transmission or reflection configuration) onto a two-

dimensional ADDA array 22, each detector/processor pair of the ADDA array having a maximum response frequency tuned to the illumination modulation frequency.

5 Fig. 5 shows a microscopy imaging apparatus according to a second embodiment of the present invention. In this embodiment, light is produced by an incoherent light source 31, before being optionally attenuated by optional attenuator 32. A periodic illumination pattern is generated by a mask 36 contained in housing 35 and located
10 at an intermediate image position conjugated to the object. The pattern is imaged onto specimen 39 via the objective lens 40 of a conventional microscope observation optics 41. The mask is moved laterally by a piezo-element (not shown) to shift the image of the illumination pattern relative to
15 the specimen. The observation optics then form an image of the specimen from scattered or emitted light at a two-dimensional ADDA array 42 located at a conjugate image plane.